IMAGING THE ANISOTROPIC ELASTIC PROPERTIES OF PAPER WITH THE INEEL LASER ULTRASONIC CAMERA

V. A. Deason, K.L. Telschow, R. S. Schley and S. M. Watson
Idaho National Engineering and Environmental Laboratory
Lockheed Martin Idaho Technologies Co.
Idaho Falls, ID 83415-2209

INTRODUCTION

The paper industry has long used ultrasonic Lamb waves for off-line inspection to determine the stiffness distribution in paper[1]. Numerous efforts have been made, with varying levels of success, to bring such measurements on-line. Recently, the Idaho National Engineering Lab (INEEL) and the Institute for Paper Science and Technology (IPST) collaborated on a project to adapt laser ultrasonic inspection techniques to on-line measurements of paper properties. This paper describes one aspect of that project performed at the INEEL: the development of an imaging approach to ultrasonic inspection of paper. IPST provided characterized paper samples and guidance on paper properties and production methods.

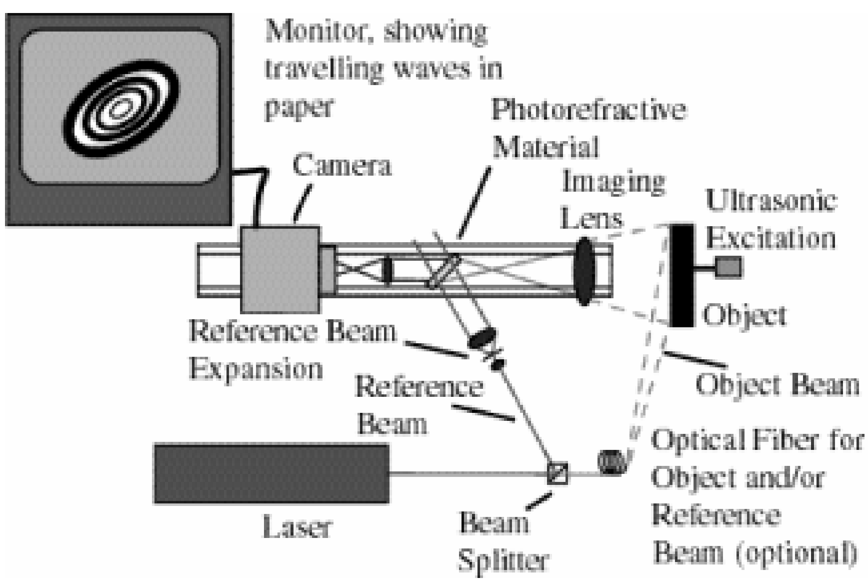

Figure 1: The INEEL Laser Ultrasonic Camera in the Two-Wave Configuration

The INEEL Laser Ultrasonic Camera utilizes non-linear photorefractive materials as sensors to detect surface vibrations through dynamic holographic interferometry. The method uses coherent laser illumination and interferometry to record the ultrasonic vibration location and amplitude on a surface. In this method, a time varying hologram is stored in the photorefractive material as photo-generated space charges that alter the index of refraction of the material through the linear electro-optic effect. Subsequently, the hologram is reconstructed to generate a light beam whose intensity is proportional to the amplitude of the vibrations[2,3,4,5,6]. A typical layout for the camera is shown in Figure 1.

EXPERIMENTAL SETUP

Characterized paper samples were mounted in a 150 mm diameter ring and the lowest order antisymmetric Lamb wave mode was continuously excited at the center of the back surface of the paper by contact with a piezoelectric transducer. These waves typically attenuated before reaching the ring support, so only outward traveling waves were seen. The INEEL Laser Ultrasonic Camera was used to image the Lamb waves from the front of the paper. A sequence of frames shows the motion of the waves as they travel out from the central excitation point as shown in Figure 2. The shape of the acoustic wavefront can be used to determine the acoustic velocity in any direction, as well as the presence of inhomogeneities and defects. Paper ranging in color from white copy paper to brown cardboard liner stock was tested. All surfaces were diffusely reflecting and were measured in the as-received condition.

EXPERIMENTAL MEASUREMENTS

Each image of the Lamb waves shows a pattern of concentric rings corresponding to the ultrasonic wavefronts on the paper. If the paper properties were isotropic, these rings would be circular. However, most paper is anisotropic in stiffness, so the rings were oblong, with the major axis aligned with the maximum stiffness direction

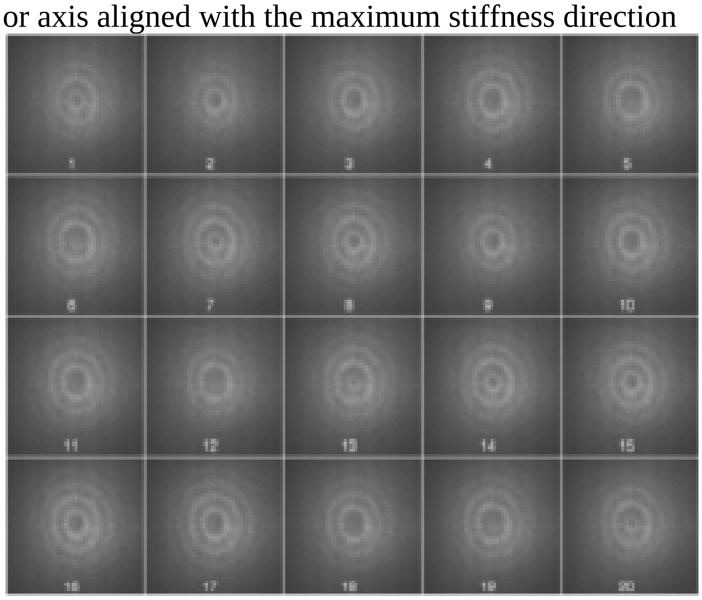

Figure 2: Sequence of frames from Laser Ultrasonic Camera recording of traveling waves in paper

(usually the production machine direction (MD), while the minor axis is aligned with the machine cross direction (CD). Minor deviations from these directions can occur due to irregularities in the paper making process, and the ratio of MD to CD stiffness depends on the paper production process.

Fourier transforms (FT) provide a convenient method to quickly extract relevant information from INEEL Laser Ultrasonic Camera images. The magnitude of a two dimensional FT displays the spectral power distribution as a function of spatial frequencies in all directions. For a typical Lamb wave image with several wavefronts visible, one will see a single point along each direction that represents the dominant spatial frequency in that direction (Figure 3).
When all directions are displayed, a single ring is produced whose major/minor axis ratio and major axis direction are a result of the wavefront information seen in the original image. The ratio and orientation of the Lamb wave speed and hence paper stiffness can be easily extracted for all directions at once from a single INEEL Laser Ultrasonic Camera image.

The images provide other information, as well. Distortions in the wavefronts as they propagate, provide information about distributions of defects, local composition and thickness variations. A single image is therefore capable of providing substantial information about the paper properties and condition. While the data shown here typically measure in-plane properties, it is possible to configure the INEEL Laser Ultrasonic Camera to measure out-of-plane properties.

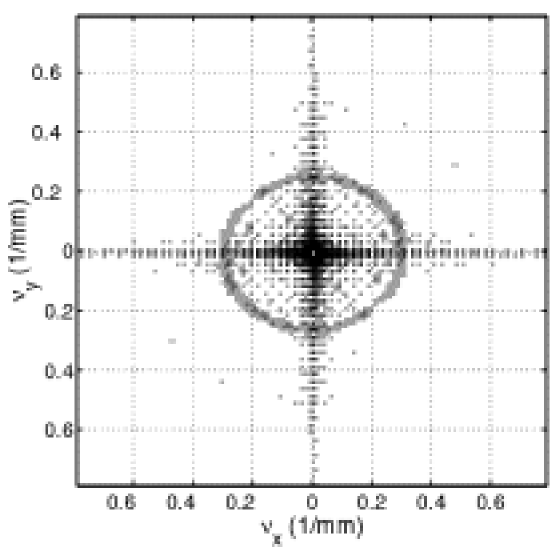

Figure 3: Corresponding FFT from image of traveling waves in paper

Measurements were taken on an IPST RSK59 sample with an analog video camera and 8-bit video digitizer. IPST provided physical properties and all but two of the anisotropic elastic constant matrix values for these paper samples. The remaining two were estimated using data for comparable materials. These values are shown in table 1. Using these values, and appropriate plate mode theory[1], the wavelengths of the A_0 and S_0 modes as a function of frequency were computed for both machine and cross directions. The results for a 112 µm thick RSK59 paper sample in both the MD & CD (using table 1 data provided by IPST) are also shown in Figure 4.

Table 1: Anisotropic elastic constant matrix values for paper sample RSK59

RSK59 (data from IPST): 59 lb. rawstock
Density = 0.818 g/cm^2
Thickness = 110 _m

Cmatrix (GPa)

9.85	1.77	0.10	0.00	0.00	0.00
1.77	4.95	0.15	0.00	0.00	0.00
0.10	0.15	0.14	0.00	0.00	0.00
0.00	0.00	0.00	0.20	0.00	0.00
0.00	0.00	0.00	0.00	0.21	0.00
0.00	0.00	0.00	0.00	0.00	2.53

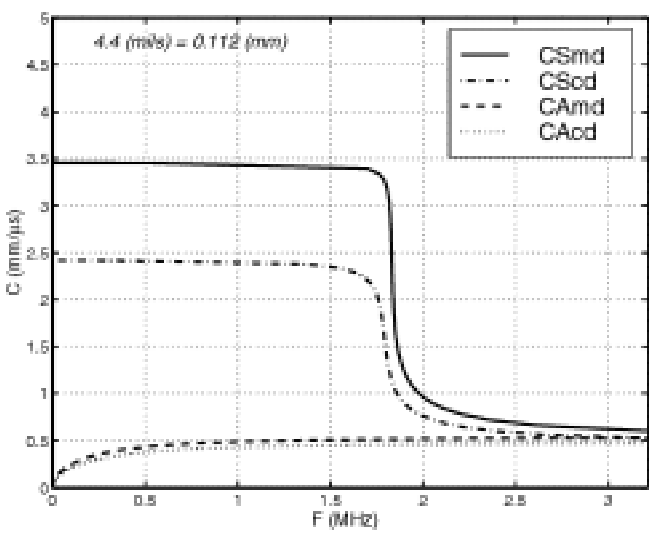

Figure 4:Calculated A_0 and S_0 mode velocities for paper sample RSK59 in the cross and machine directions

Normally one obtains the MD/CD stiffness ratio using the S_0 ultrasonic modes as no dispersion occurs for this mode at low frequencies. However, experimentally, the A_0 mode is easier to excite and is typically an order of magnitude larger in amplitude than the S_0 mode. Since only a single frequency is used for the INEEL method, the dispersion of the A_0 mode is unimportant. The imaging INEEL approach is therefore able to utilize the advantages of this mode as dispersion is no longer present at low frequencies. Wavelengths computed from the INEEL method and for these paper types using the elastic data provided independently by the IPST are shown in Figure 5. Very good agreement with the experimental data is evident, which illustrates the quantitative capability of the imaging ultrasonic method.

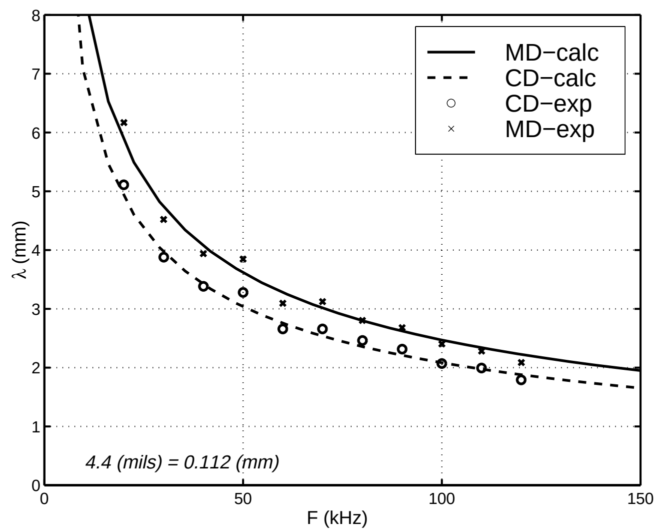

Figure 5: Comparison of calculated and experimental wavelength data for sample RSK59 in MD and CD

MD/CD STIFFNESS RATIO DETERMINATION

It has been traditional to use the S_0 modes for determination of the MD/CD stiffness ratio due to the nondispersive nature of this mode. For the S_0 mode in a plate of thickness h, the wavevector is

$$k_{S0} = \frac{2\pi}{\lambda_{S0}}, \quad \text{for } k_{S0}h << 1 \quad \Rightarrow \quad h << \frac{\lambda_{S0}}{2\pi}$$

the phase velocity is given by

$$C_{S0} = \frac{\omega}{k_{S0}} = f\lambda_{S0} \approx \sqrt{\left(\frac{C_{11} - C_{13}^2 / C_{33}}{\rho}\right)} \equiv C_0 \quad \Rightarrow \quad \left[\ \lambda_{S0} = \frac{C_0}{f}\ \right] \tag{1}$$

The square of measurements of CS0 in both the MD & CD directions yields the MD/CD stiffness ratio.

However, the A_0 mode can be used also at low frequencies. For the A_0 mode in a plate of thickness h, the wavevector is $k_{A0} = \frac{2\pi}{\lambda_{A0}}, \quad \text{for } k_{A0}h << 1 \quad \Rightarrow \quad h << \frac{\lambda_{A0}}{2\pi}$ the phase velocity is given by

$$C_{A0} = \frac{\omega}{k_{A0}} = f\lambda_{A0} \approx \frac{k_{A0}h}{\sqrt{3}}\sqrt{\left(\frac{C_{11} - C_{13}^2/C_{33}}{\rho}\right)} = \frac{k_{A0}hC_0}{\sqrt{3}} = \frac{2\pi hC_0}{\lambda_{A0}\sqrt{3}} \tag{2}$$

with the consequence that the wavelength $\lambda_{A0} = \sqrt{\frac{2\pi hC_0}{f\sqrt{3}}}$ and

$$\lambda_{A0}^2 = \frac{C_0}{f}\left(\frac{2\pi h}{\sqrt{3}}\right) = \lambda_{S0}\left(\frac{2\pi h}{\sqrt{3}}\right) \quad \text{or} \quad C_{A0}^2 = \left(\frac{2\pi fh}{\sqrt{3}}\right)C_{S0}. \tag{3}$$

Therefore, the square of the MD/CD ratio for the A_0 mode can yield the same information about

$\left(\frac{C_{11} - C_{13}^2/C_{33}}{\rho}\right)^2$ as the S_0 results, since $\frac{C_{S0}(MD)}{C_{S0}(CD)} = \frac{C_{A0}^2(MD)}{C_{A0}^2(CD)}$

$$\frac{C_{S0}(MD)}{C_{S0}(CD)} = \frac{C_{A0}^2(MD)}{C_{A0}^2(CD)}, \quad \text{for} \quad h << \frac{\lambda_{A0}}{2\pi}. \tag{4}$$

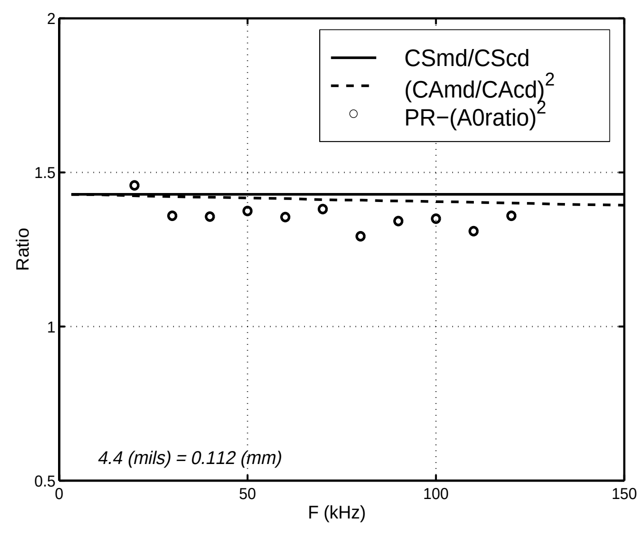

Figure 6: Calculated and experimental ratios of MD to CD velocity compared for A_0 and S_0 modes

Figure 6 shows the predicted and experimentally measured values for the corresponding ratios obtained in RSK59 paper. Good agreement is seen for all the photorefractive imaging measurements with a deviation systematically appearing at the higher frequencies, as predicted. The calculated values show the amount of deviation between the two ratios to be expected as a function of frequency and indicate that the two ratios agree to within about 4% for frequencies up to 150 kHz.

CONCLUSION

The INEEL photorefractive imaging ultrasound approach has resulted in the INEEL Laser Ultrasonic Camera, offering a new and powerful method for performing non-contact measurements of elastic waves in paper. The imaging approach provides more information and significant improvement in measurement speed compared to typical point measurement methods. Data have been provided that show the imaging method is sensitive and quantitative, yielding the complete A_0 mode wave speed anisotropy in one quickly obtained image from a CCD camera.

ACKNOWLEDGEMENTS

The authors wish to thank P. Brodeur, C. Habeger, J. Gerhardstein, E. Lafond and others at the Institute for Paper Science and Technology for characterized paper samples, and for many informative and stimulating discussions of paper physics and paper manufacturing processes. This work was sponsored by the DOE Office of Industrial Technology/Forrest Products and the INEEL Laboratory Directed Research & Development program under DOE Idaho Operations Office Contract DE-AC07-94ID13223.

REFERENCES

1. Habeger C.C., Mann R.W., and Baum, B.A., *Ultrasonics* **17**, 57 (1979)
2. T.C. Hale and K. Telschow, "Optical lock-in vibration detection using photorefractive frequency domain processing," Appl. Phys. Lett. 69, 2632 (1996).
3. T.C. Hale, K.L. Telschow and V.A. Deason, "Photorefractive optical lock-in vibration spectral measurement," Applied Optics, 111, 8248 – 8258, 1997.
4. K.L. Telschow, V. A. Deason, K.L. Ricks and R. S. Schley, "Photorefractive laser ultrasound spectroscopy for materials characterization," Nondestructive Characterization of Materials VIII, ed. R.E. Green, Jr., (Plenum Press, New York, 1998) 79-84
5. K. L. Telschow and V. A. Deason, "Structural Vibration Mode Imaging Using Photorefractive Holography," Proceedings of the 16th International Congress on Acoustics / 135th Acoustical Society of America Meeting Seattle, WA, June 20-26, 1998 pp 1873-1874
6. K.L. Telschow, V. A. Deason, R. S. Schley and S. M. Watson, " Imaging of Lamb Waves in Plates for Quantitative Determination of Anisotropy using Photorefractive Dynamic Holography," Reviews of Progress in Quantitative NDE, Vol. 18A, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York, 1998) pp 999-1005.